Combining geophysical and mechanical testing techniques for the investigation and characterization of ISC'2 residual soil profile

Combinaison de techniques géophysiques et mécaniques dans l'investigation et caractérisation du profil de sol résiduel de l'ISC'2

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ABSTRACT
This paper summarizes the results of an experimental site investigation and characterization survey, on a residual (saprolitic) soil from granite, located at the Faculty of Engineering of the University of Porto (FEUP). This project aims at characterizing these unusual soils in the context of the development of an International Prediction Event (Class A) on the behaviour of different types of piles. A very extensive site characterization campaign, including a large variety of in situ tests and field methods, has been held. These investigations comprised the application of several geophysical borehole and surface methods, namely: P and S-wave seismic refraction, reflection, cross-hole (CH), down-hole (DH), electrical resistivity imaging, ground probing radar (GPR), etc. - as well as mechanical tests - namely: SPT, CPT, DMT, among others. The site is geologically formed by an upper layer of heterogeneous residual granitic soil overlaying a rather weathered granite contacting a gneissic migmatite. Direct and indirect results from some of the referred surveys are compared between them and with some of the available geological and geotechnical information, namely those obtained from seismic, electrical and GPR profiles, conducted adjacent to three boreholes in which undisturbed soil samples were collected previously to geophysical data acquisition. In addition, an extensive laboratory testing program was carried out using the collected undisturbed samples. A discussion of the obtained results is inhere presented, giving emphasis to the correlations encountered between the different tests, specific of saprolitic soils with weak relic structures.

RÉSUMÉ
Cette communication est un sommaire des résultats obtenus lors d'une campagne d'investigation et de caractérisation d'un sol résiduel (saprolitique) de granite dans la Faculté de Génie de l'Université de Porto (FEUP). Ce projet a pour but la caractérisation de ce type de sols peu usuels, dans le contexte de la réalisation d'un Evénement International de Prédiction (Class A) sur le comportement de différents types de pilotis. Une grande variété de techniques/méthodes et essais in situ ont été utilisées dans une campagne très complète d'investigation et caractérisation du lieu. Cette campagne a inclus l'application de méthodes géophysiques depuis la surface et entre forages – par exemple: sismique, par ondes P et S, de réfraction, réflexion, cross-hole (CH) et down-hole (DH); résistivité électrique, radar de sols (GPR), etc. – ainsi que de méthodes mécaniques – par exemple: SPT, CPT, DMT, etc. Géologiquement, le lieu est formé par un sol de couverture résiduel de granite sur des formations granitiques altérées en contact avec des migmatites gneissiques. Des résultats obtenus directement et indirectement de quelques-unes des techniques utilisées sont comparés entre eux et avec l'information géologique et géotechnique disponible. En particulier les résultats obtenus à partir de profils sismiques, électriques et electromagnetiques (GPR), réalisés à côté de trois sondages carottés dans lesquels des échantillons non perturbés ont été recueillis avant leur utilisation pour des essaies sismiques. Un programme très complet de tests de laboratoire a été conduit en utilisant les échantillons non perturbés. Une discussion des résultats obtenus est ici présentée, en particulier sur les corrélations identifiées entre les différents tests, spécifiques de ce type de sols saprolitiques de faible signature structurelle originale.

1 INTRODUCTION

Residual soils from granite are very common in the northwestern part of Portugal where ISC'2 experimental site is located within the campus of the Faculty of Engineering of the University of Porto (FEUP). The site is geologically formed by an upper layer of heterogeneous residual (saprolitic) granite soil of varying thickness, overlaying more or less weathered granite contacting high grade metamorphic rocks.

The thickness of these residual saprolitic horizons may vary between few meters to more than 20m. Although they often present strong heterogeneity, it is frequently observed an average gradual change of characteristics with depth, namely regarding their manifested mechanical properties. Nevertheless, an accurate mapping of the spatial variability of the mechanical properties, necessary for geotechnical design is often challenging.

The data compiled during the extensive in-situ and laboratorial investigation and characterization of ISC'2 experimental site, comprising the application of several geotechnical and geophysical surface and borehole techniques, namely SPT, CPT, DMT, surface and borehole seismic, electrical resistivity, and GPR, is a valuable opportunity to compare different methodologies and assess their relative advantages and limitations.

2 GEOLOGY

The ISC'2 experimental site is located in a contact zone between the gneissic rocks and the granite mass. The type of regional transition between the two bodies is not a single discontinuity surface but a gradual one, consisting of an eastward "probabilistic" decreasing of feldspar bands maintaining the geological planar anisotropy, with constant strike and dip, but with frequent zones of abrupt lithologic changes. The weathering process tends to transform the feldspar into kaolin mainly in the geological contact zones where namely later fluid weathering action was more intense. Typical Porto granite is a leucocratic alkaline rock, medium to coarse grained, with megacrystals of feldspars and two micas. The mineralogical constitution of this rock varies generating a fairly heterogeneous mass.

3 GEOPHYSICAL CHARACTERIZATION

Direct and indirect results from geophysical surveys were compared between them, as well as with some of the available geological and geotechnical information (Carvalho *et al.* and Almeida *et al.*, 2004), namely those obtained from: P and S-wave conventional (RC) and tomographic (RT) refraction, high resolution shallow reflection, CH, DH, electrical resistivity and GPR. The layout map of the site, in Figure 1, shows the location of the seismic and electrical resistivity imaging traverses. CH data acquisition took place between boreholes S1-S2, S2-S3 and S1-S3. In borehole S3, a P and S-wave DH seismic survey was conducted, with 1.5m interval between shots.

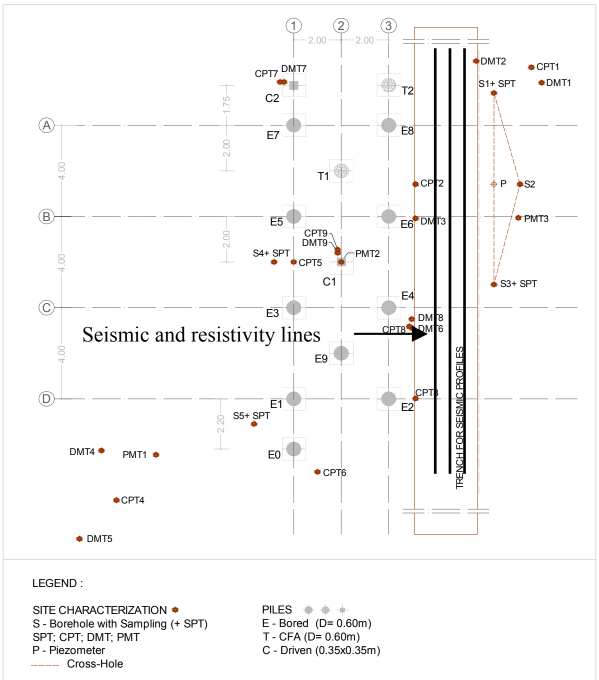

Figure 1. Layout of ISC'2 experimental site.

Seismic refraction data acquisition was performed along a 44.5m long traverse, having 1.5m meter spacing between geophones and nine shot points.

The generic S and P-wave travel time pattern points out to an average gradual increase of velocity with depth. The P-wave velocity, V_P, section resulting from tomographic inversion is presented in Figure 2 and in Figure 4 is the S-wave velocity, V_S, section resulting from tomographic inversion, overlaid by the obtained Time Delay method three layers model (dotted lines).

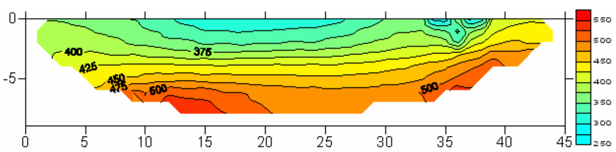

Figure 2. V_P refraction tomography section.

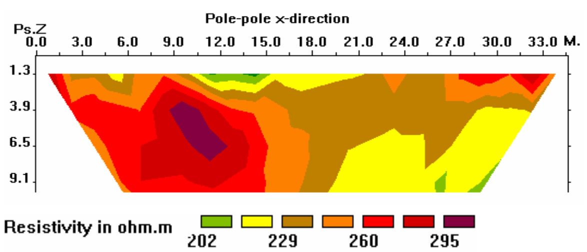

Figure 3. Electric resistivity image section.

An electrical pole-pole imaging survey was developed parallel to the seismic refraction traverse. One of the two obtained inversion interpretation method sections is shown in Figure 3.

The overall pattern of seismic velocity variability matches the one obtained with electric resistivity: in both interpretations a sub-vertical transition can be seen on the right side of the section, separating zones of overall different apparent resistivities. The lower resistivity value zone, on the right side, corresponds to a higher seismic velocity zone signed by RC sections and confirmed most notoriously in RT S-wave section.

The high resistivity anomaly above water level (referred below) is interpreted as being related to a lower kaolin band dipping 60º eastwards. The high RT V_S (also below) is well correlated with that high resistivity anomaly. The lower V_S zone in the middle of the profile is interpreted as a clayey band due to the fact that V_P do not change significantly along the horizontal direction therefore, within this lower V_S zones, Poisson ratio will increase to a clayey domain.

The RC method show two interfaces (dotted lines in Figures 4 and 5) where velocity changes: the lower one is interpreted as being related to seasonal water level and the upper one is very consistent namely with the tomographic and reflection velocity fields as well as with GPR results (also in Figures 4 and 5). In this processed radargram, a reflector is visible with very good agreement with the first interface of the RC model; the N_{SPT} values increase between 3m and 4m deep which supports the existence of a transition zone. There are some visible diffractions, and possibly a less weathered zone between 0m and 5m along the transect line, from the surface to 3.5m depth.

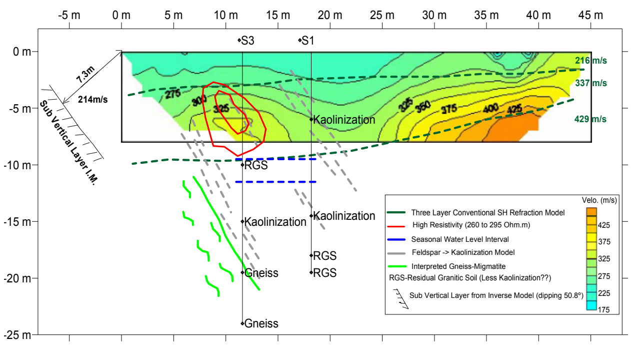

Figure 4. 2D seismic RT V_S model (m/s) overlaid by other geophysical results (Carvalho *et al.*, 2004) and hypothetical geological model used for seismic reflection interpretation (Almeida *et al.*, 2004).

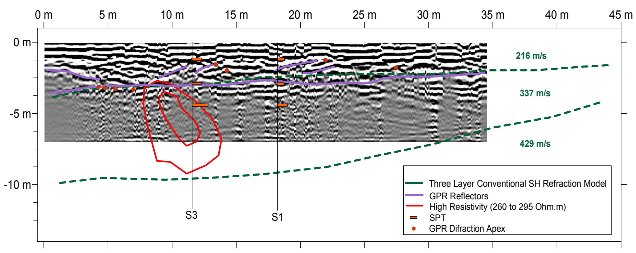

Figure 5. Processed radargram with interpreted events overlaying the resistivity and RC model and N-SPT values in boreholes S3 and S1.

In order to evaluate the response of the site to reflected S waves, a reflection profile was done after a walk way noise test. Following the processing procedures, the next step was to overlay all the information interpreted from seismic reflection, refraction, resistivity, GPR and from the geology (Figure 6).

In Fig. 6a), the interval velocities obtained from CMP analysis are overlaid by the RC three layers model, the high resistivity contour lines and the hypothetical lateral dipping structure model (dip: 50.8ºE) obtained from seismic side reflections. This model is believed to be related to the identified 60ºE dipping gneissic-migmatite local structures. In Fig. 6b), the seismic stacked section obtained is overlaid with interpreted seismic and GPR information.

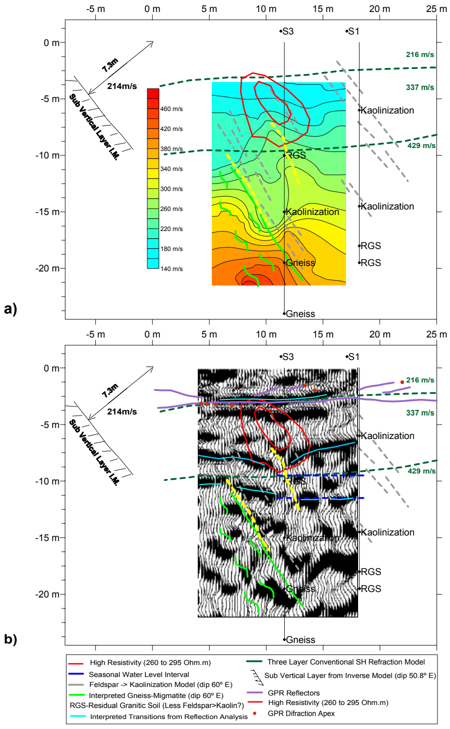

Figure 6. Integration of the interpreted partial models: a) interval velocity model; b) stacked seismic reflection section.

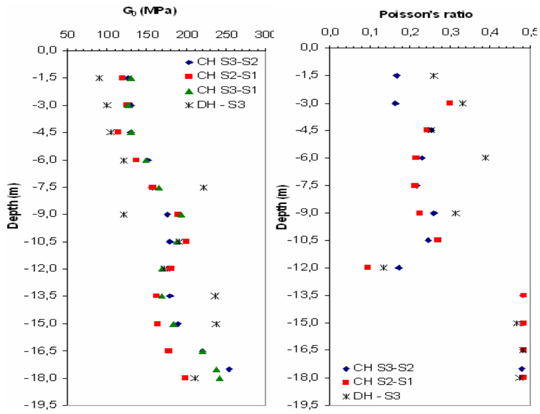

Figure 7. Shear modulus and Poisson ratio: CH and DH profiles.

4 GEOMECHANICAL CHARACTERIZATION

In spite of the complex natural spatial variability of the fabric of these residual soils, due to some preserved relic heritage, there is evidence of a fairly homogeneous ground profile in geotechnical terms, as demonstrated by results obtained with continuous sampling from drilling, with the SPT sampler (description in Viana da Fonseca *et al.*, 2004).

The first stage of the site characterization included 4 SPT, 5 CPTU, 5 DMT and 3 PMT while in the second stage were performed 4 CPTU and 4 DMT. The technical data of the first stage of in situ tests were summarized in Viana da Fonseca *et al.* (2004). Results derived from the CH survey are included in Figure 7 (G_0 and ν values). Data acquisition took place in July (dry season, with around 10m piezometric readings). G_0 and V_S variability with depth follows a similar pattern, smooth in general although more erratic in the case of DH based values.

The ν values show in general higher dispersion except in the saturated zone below 13.5m. While in the zone above 13.5m the values vary around an average value of 0.25, below that level they are quite constant with values near 0.5 (around 0.48). This is an obvious sign of full saturation.

5 GENERAL TRENDS AND CORRELATIONS

Some correlations have been derived form the available database and described elsewhere (Viana da Fonseca *et al.*, 2004, Carvalho *et al.*, 2004). Values of $(N_1)_{60}$, taken from the SPT tests, allowed to derive the angle of shearing resistance from Décourt's (1989) proposal, ranging from 35º to 41º, with an average of 38º. This value coincides with those reported in similar regional soils, namely for Porto silty sand (Viana da Fonseca, 2003).

The general classification by Robertson (1990) chart identifies this material as cemented and aged, with a grain size distribution from silty clays to clayey sands. Lab tests over recoiled samples have confirmed it mainly as clayey silty sand.

The relation between q_c from CPT and σ'_{v0} is presented in Figure 8, which integrates Robertson and Campanella's (1983) curves for the estimation of the angle of shearing resistance. The CPT results reveal a moderate increase of q_c in depth. Robertson and Campanella's proposal tends to higher values of ϕ', especially at lower depths, than those obtained from triaxial tests, since the cohesive component is not considered. This reflects the simultaneous sensitivity of q_c towards frictional and cohesive components. In the present case, the CPT results are rather constant in depth, crossing a wide range of friction angles (35-42º) with more incidence at 37º, which is much lower than the one obtained in the laboratory tests.

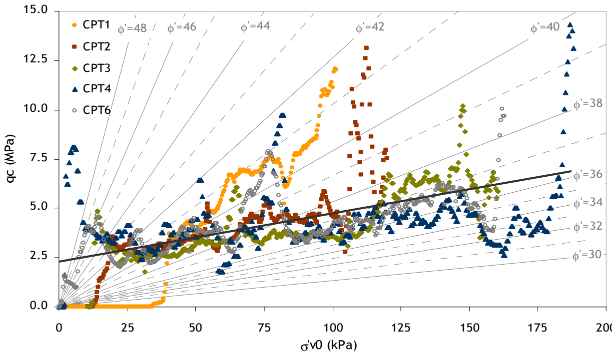

Figure 8. Relation between q_c and σ'_{v0} values, and the angle of shearing resistance, ϕ' (Robertson and Campanella, 1983)

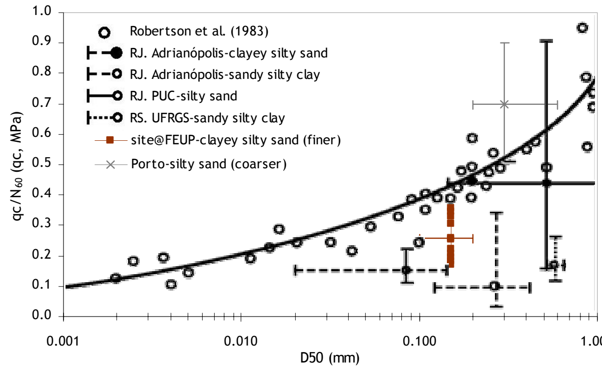

Figure 9. Ranges of q_c/N versus D_{50} on Brazilian residual soils, compared with the experimental site results (based on Danziger *et al*, 1998)

This is a consequence of the cohesive-frictional soil behaviour, where the lower confinement levels are dominated by the cohesive component, while the higher are governed by friction.

The usefulness of correlating results from SPT and CPT tests, led to the evaluation of q_c/N_{60} ratio and its dependence on the mean grain size, D_{50} (Robertson and Campanella, 1983). For the case of the experimental site, this ratio varied from 0.17 to 0.36 (D_{50} = 0.15 mm – Fig. 9). Present data are in close agreement with Brazilian data (Danzinger *et al.*, 1998), but contradictory with Porto silty sand data. This is probably a consequence of the more intensive clayey content of the soil. Preliminary analyses of DMT and PMT results enabled the soil identification. For instance, DMT I_d graph classifies it as a silty sand to silt, corroborating the results of the penetration tests (Viana da Fonseca *et al*., 2004).

The results of S-wave CH tests are very consistent and reveal a very smooth increase of the small strain shear modulus, G_0, with depth. The variation of G_0 with mean effective stress, p'_0, taking due consideration of the void ratio function in depth and the necessary normalization of this G_0 to the void ratio function, conducted to the following proposal:

$$\frac{G_0}{F(e)} = A \cdot p'_0{}^m = 110 \cdot p'_0{}^{0.02} \tag{1}$$

where $$F(e) = \frac{(2.17 - e)^2}{1 + e} \tag{2}$$

The value of the constant for the G_0 expression is much higher for these residual soils (A=110) than for sandy transported soils (A=7.9 to 14.3), in natural alluvial sands, aged and cemented (Ishihara, 1982), while the exponent m, reflecting the influence of the mean effective stress, is substantially lower. For Porto silty sand, Viana da Fonseca (2003) found different constants, as illustrated in equation (3), which describe a slightly higher dependence of G_0 on p_0'. This may result from the fact that the saturation conditions of these soils are very different.

$$\frac{G_0}{F(e)} = 65 \cdot p'_0{}^{0.07} \tag{3}$$

Correlations between N_{SPT} and stiffness are very sensitive to different factors, while those relations between penetration parameters and G_0 are somewhat independent of misleading factors, such as scale effects, non-linearity, etc. A power law between G_0 and N_{60} was obtained, where only the SPT results from the boreholes nearest to the CH tests (S1 and S3) were considered:

$$G_0\,(MPa) = 63 \cdot N_{60}{}^{0.30} \tag{4}$$

Correlations between q_c and G_0 are very influenced by cementation and ageing. Robertson *et al.* (1995) suggested a chart based on normalized cone resistance Q_t and G_0/q_c which allows for the identification of "unusual" soils such as highly compressible sands, cemented and aged soils and clays with either high and low void ratio. This chart is presented in Figure 10, together with our results.

V_S measured in situ, via CH tests, and in the laboratory, with bender elements or in the resonant column, were compared. The similarity of V_S trends in depth from both in situ and laboratory tests is evident and the differences encountered may well be mainly due to the disturbances associated to sampling. This is discussed elsewhere (Viana da Fonseca *et al*., 2004).

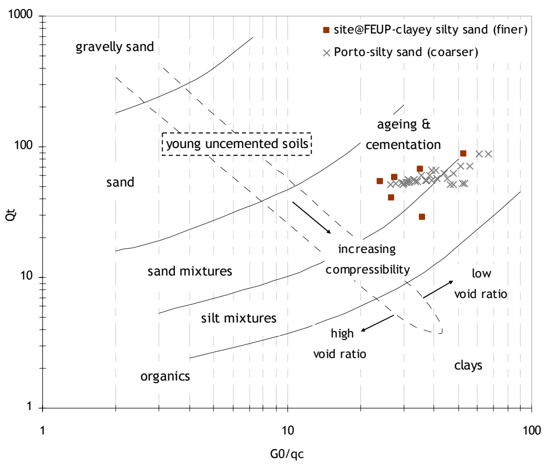

Figure 10. Classification based on Q_t vs G_0/q_c (Robertson *et al*., 1995)

6 CONCLUSIONS

The extensive site investigation/characterization carried out at the University of Porto ISC'2 experimental site has enabled the determination of the most relevant geotechnical properties of this soil profile, as well as to derive and to compare the obtained correlations with other proposals referring to residual soils.

This paper summarizes the overall trend of conducted mechanical in situ tests and the application of geophysical surface and borehole methods to ground characterization and mapping.

This residual saprolitic soil from granite was classified, under classical terms, as clayey silty sand and this assumption is supported by the results of the various tests.

One of the relevant conclusions is the similarity in the spatial correlation presented by seismic and electrical section models as well as the very consistent similar horizontal interface pattern common to interpretative models from seismic stacked section, conventional refraction and GPR radargram. Also, the SH wave velocity fields (cross-hole, reflection and refraction) and resistivity model support the local geological evidence.

Tentative geological interpretation models, integrating information namely from S-wave refraction, high resolution shallow reflection and GPR surveys, were presented.

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